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Learning from Javanese vernacular theater architecture: passive natural ventilation strategies in a tropical humid climate

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Abstract
Tropical vernacular heritage buildings serve as repositories of generations of embodied climate wisdom, yet their passive environmental performance remains poorly documented. The research explores the thermal performance and natural ventilation strategies of the Sobokartti Theatre in Semarang, Indonesia. This theater is a conserved heritage building of Javanese origin and features a hybrid colonial vernacular spatial layout that combines the Joglo and Limasan typologies of the roof. The research uses a five-lens triangulation framework consisting of archival analysis, in situ observation, quantitative field measurements, computation-al fluid dynamics (CFD) simulation, and thermal comfort assessment utilizing PMV, ASHRAE Standard 55, and the Indonesian National Standard (SNI). Field measurements showed mean interior air velocities of 0.54–0.68 m/s and in-let-to-outlet temperature differences of 0.7–1.1°C. The multistage Joglo roof acts as both a wind scoop and a stack-effect driver, resulting in aperture velocities of 0.40–0.53 m/s. The CFD simulation proved the conceptualized thermal moderation of a vertically arranged air flow system. Even when PMV values reached 2.1–2.2 during peak hours, thermal tolerance of occupants was between 72% and 89%, indicating a significant adaptation capability of users of tropical buildings. The building's environmental performance is the result of a coherent interplay between the configuration of vernacular architecture, natural ventilation and the relationships between the occupants and the environment. This paper proposes a replicable framework for the assessment of naturally ventilated heritage buildings as integrated environmental systems. It argues that conservation should not be only about physical authenticity but also about the transmission of embedded climatic intelligence for the sustainable low-energy design of architecture.

Keywords: Natural ventilation; Thermal comfort, Heritage building, CFD simulation, Tropical climate, Sobokartti

1. Introduction

Indonesia is a country with high cultural diversity and ethnic pluralism. The Javanese culture is one of the wealthiest and most miscellaneous which was configured across the synthesis of elements of pre-Hinduism, Hindu-Javanese, Islam, and other beliefs along with the inclusion of various religions such as Islam, Christianity, Buddhism, and Hinduism [1]. Diversity of architectural configuration also found in this nation established in communal Austronesian heritage [2]. Regarding the affluent cultural history, multiplicity of the landscape, and the necessity of conserving traditional building techniques, the exploration of Indonesian vernacular architecture is essential with the aim of recording the peculiar features, construction methods, and material used in the diverse archipelagic territory [3]. It passed over generations of cultural relics with incomparable topologies, shapes and local materials. Nevertheless, the empirical data concerning vernacular architectural patterns is still circumscribed; however, these traditions are mostly turned over orally and often embrace factors of local beliefs.

A deliberate and eco-friendly response to native surrounding conditions was depicted in vernacular architecture. The historic buildings perform the function of architectural literature reference and the reflection of adaptive wisdom with regard to thermal performance by way of native material employment in accord with the native climatic framework. This is particularly relevant to Indonesia's architectural heritage, where the traditional building structure was designed to respond to the tropical humid climate.

Centuries of Dutch colonization in Indonesia had a profound impact on many aspects of Indonesian society, both explicitly and implicitly, arising from education, language, culture, and architectural evolution. Modern influences on Indonesian traditional architecture actually began during the Dutch colonial era. Some practicing architects at the time started expressing a desire to incorporate colonial Dutch modernism with traditional architectural details; one of them was Thomas Karsten. He has completed several projects, including residences, schools, hospitals, train stations, market-places, theatres, and office buildings. Those designs incorporate a blend of classic and modern architecture.

The Dutch government built buildings in various major cities in Indonesia in European architectural style, which is recognized as Dutch colonial architecture. The tropical humid climate of Indonesia was the main consideration in the designs, which emphasized the use of natural ventilation for providing indoor comfort and artistic apparatus. As the location of Semarang city was very strategic for the Dutch government, making this city a center for government, trade and art. One of the structures built by the Dutch colonial government which is still used by the natives is Sobokartti. It was constructed by the Dutch colonial government as the response to the ethical politics that were being broadly encouraged in the Netherlands at that time. The ethical political movement gave indigenous people the opportunity to access education and arts, which eventually resulted in the formation of an art community named Sobokartti, consisting of members from Javanese, Dutch, and Chinese communities.

The study of historical structures revealed valuable comprehension of the implementation of sensitive design strategies for building ventilation systems [4]. Currently, exhaustive documentation of passive design strategies in vernacular architecture is quietly insufficient and has need of systematic scientific awareness. It lays the groundwork for an investigation that attempts to methodologically investigate the correlation between the surrounding atmospheric conditions, topographic features, and the style of vernacular architecture on Java's First People Theatre. The aim is to probe how the design features of this building ease natural ventilation in regard to comfort, with a focus on the architectural configuration of this legendary building.

1.1. Javanese vernacular architecture

The roots of vernacular architecture are naturally vigorous and constantly developing in response to the transformation of materials, technology, and human knowledge. The architectural longevity of vernacular architecture depends on the synthesis of environmental, technological, and cultural elements, which include geography, climate, building strategies, philosophy, religion, and socio-economic conditions, serving both as a response to contemporary changes and as a reflection of community cosmology and behavior patterns [5].

Javanese traditional architecture places the greatest culturally substantial element of Java. The customary Javanese house functions not simply as a personal residence but also conveys a more com-prehensive societal role in Javanese culture. Symbolic, sociological, and architectural figures assemble in a construction uniquely conforming to the natural ambience, indigenous culture, and domestic climate. Research reveals that the traditional Javanese house does not work merely as a physical house; furthermore, it is a depiction of the fundamental philosophy and intention of its natives [6]. Particularly, traditional Javanese dwellings share identical spatial layouts; roof shapes vary in line with the social status of the proprietor, reflecting the cultural values and social hierarchies within Javanese society. Additionally, the design of Dutch colonial architecture had a significant influence on Javanese traditional architecture, which subsequently con-tributed to the evolution of modern architecture in Indonesia around the twentieth century [7]. The intensely essential factor affecting building amenities is thermal comfort. Fanger [8] stated that comfort is essentially deep-rooted in psychological occurrences rather than simply physical or atmospheric ambiences, with air temperature, humidity and air movement working as the principal climate parameters that control prime thermal conditions.

Elevated temperature, humidity, precipitation, and a steadily weak wind rate are the characteristics of Indonesia's tropical humid climate, which provides noteworthy requirements for attaining acceptable thermal comfort [9]. The native environment fundamentally influences thermal performance, a feasible means of control proposed by architectural designs. Building orientation and the arrangement of apertures are key factors in thermal planning [10], reflecting a long-standing principle in native Javanese knowledge regarding the harmonious alignment of buildings with nature.

The primary focus of Javanese architectural configuration is to provide indoor thermal comfort, which is evident in the building layout, aperture formations, and ventilation systems. Facade openings are the main way to control the temperature, relative humidity, and airflow speed inside a building. Previous research has shown that natural ventilation can improve indoor thermal comfort in tropical climates [11]. Climate-responsive design is central to achieving thermal comfort. Buildings in the tropics are characterized by low thermal mass to prevent heat retention into the evening, combined with high ventilation orientated toward prevailing winds. It was reinforced collectively by wide openings, windows, and doors [12].

Passive design strategies in traditional Javanese buildings propose a valuable model for deliberating the persistent hot conditions that occur in the tropics, where these methods surpass modern construction in passive thermal performance [13]. This strategy is customarily used to provide in-door thermal comfort by regulating sunlight access to the building, aiming to optimize indoor air quality while respecting landscape management, building orientation, materials, roof design, and façade configuration [14].

1.2. Javanese vernacular architecture and ventilation system strategy

Environmentally conscious and resilient designs with passive methods commonly tied to ameliorate indoor thermal comfort are identified as the character of vernacular architecture [15], [16] and the spatial alteration indicating comprehensive mode of living switch [17]. Vernacular structures stand for a treasured heritage for sustainable development on account of its close relation to the surrounding nature, especially the climate. The adaptation to atmospheric condition supplies occupants with superior thermal comfort than contemporary buildings [18].

Harmonization with the tropical humid climate is implemented in mostly traditional houses [19] such as Rumah Gadang (Gadang House) in Sumatera, Rumah Joglo (Joglo House) in Java, Rumah Tongkonan (Tongkonan House) in Toraja, and Rumah Honai (Honai House) in Papua, where the advanced passive design systems were, by way of ecological assessment, in fact, before modern green architecture was identified as a formal discipline. The climate of Indonesia, characterized by high temperatures, humidity, and solar radiation, makes natural ventilation systems essential in vernacular structures [20].

The evidence of sustainable development which applied in vernacular architecture is supported by natural ventilation. It contributes to regulate indoor thermal comfort and air quality without the mechanical methods [21],[22]. In addition, parameters such as building alignment, roof shapes, and opening configuration should be taken into account due to their considerable influence [23], [24]. Primary parameters which immediately rule sustainable building design are air temperature, humidity, airflow pattern and solar radiation as the climatic characteristics of neighboring circumstances, which have an enormous effect on building thermal environment and energy performance [25].

Retaining distinguishable architectural, sociocultural and representative features brings the Javanese house to be one of the highly popular Indonesian vernacular typologies. A well-measured response to the native climate and atmosphere signifies domestic environmental knowledge. Natural ventilation is the foremost passive strategy in these buildings, which has been recorded in several investigations [26]. The window-to-wall ratio (WWR) and arrangement are the key factors in ventilation enhancement. Thus, the Javanese vernacular building is remarked upon in the spacious and open ground plan with an elevated ceiling to intensely boost air circulation and passive cooling, diminishing reliance on mechanical equipment. Besides, indoor thermal performance is promoted by building orientation that sways solar heat gain as well as maximizing natural ventilation.

1.3. Brief overview of Sobokartti building

The outstanding thermal achievement of ancient buildings by utilizing native ingredients and the assimilation of the surrounding nature in an adaptive design is the essence of architectural knowledge. The tropical humid climate definitely established the venerable Indonesian buildings, similarly to customary structures outlined by surrounding nature. Sobokartti was constructed as a depiction of ethical politics to open up schooling and artistry to the natives. The stance of an artis-tic community served as an action following the construction of this building, composed of Javanese, Chinese and Dutch members, with the main objective of presenting native Javanese performing arts. Herman Thomas Karsten, as the architect, designed the building by blending the two ultimate customary Javanese roof shapes, the Joglo and the Limasan, with multistage roofs (tumpeng sari), inspiring a vernacular impression while remarking on the linkage between performing arts and the Javanese community. A prior study stated that the Joglo roof symbolized the peak of Javanese architectural tradition, while Limasan was preferred for its convenience and capacious shape [27]. The structure is compatible with the humid tropical climate because of its excellent thermal attributes. Each passive element was assessed in this investigation focused on decreasing the aver-age or peak indoor temperature, as illustrated in Figure 1 below.

2. Research method

2.1. Design of the study

Findings from qualitative research based on observation and archival investigation and only interpretive and contextual analysis are not empirically validated for assertions about environmental performance and are vulnerable to researcher bias [28]. This work solves this limitation with a mixed-methods triangulation methodology that systematically integrates qualitative architectural investigation with rigorous quantitative building science evaluation.

The aim of this study is to evaluate the thermal behavior and the passive ventilation efficiency of the Sobokartti Theatre, using a combination of three complementary research methods: (1) archival and documentary analysis, (2) ethnographic field observation and stakeholder interviews, and (3) systematic quantitative environmental measurement, which is further supported by Computational Fluid Dynamics (CFD) simulation, thermal comfort assessment and benchmark comparison. The study intends to validate and expand upon current architecture research by linking each chosen passive ventilation strategy with quantitative thermal and airflow data gathered under real tropical humid climate conditions. Triangulation is considered a valid way to support qualitative assessments with measurable environmental evidence in architectural heritage research.

The research was carefully constructed in a way to systematically generate scientific evidence from different convergent sources rather than depending on a single analytical approach. The historical and typological foundation was established through archival and ethnographic evidence; the empirical basis for indoor environmental performance was provided by field measurements; the governing airflow mechanisms were elucidated through CFD simulation; the implications for occupants were assessed in terms of thermal comfort assessment; and the broader contextual understanding of the findings was enhanced through architectural interpretation and benchmark comparison. This sequential and integrative approach enabled the assessment of environmental performance by converging information rather than isolated observations. The approach was structured in five successive steps: selection of the study object, field measurement, numerical modelling, thermal comfort assessment and integration of results. Each phase generated a different layer of information that together contributed to the gradual construction of the scientific interpretation presented in the Results and Discussion. This methodological approach was developed to improve the reliability, transparency and interpretative rigor of the study outputs.

2.2. Object of the study

The investigation was performed on Sobokartti Theatre, a naturally ventilated tropical heritage building formally declared a protected cultural asset in Semarang, Central Java, Indonesia. The building was selected because it retains the original architectural design and is operated mostly by passive environmental methods, without the need for mechanical air conditioning equipment. These attributes provide a scientifically credible opportunity to study the adaptation of the traditional Javanese vernacular architecture style to current tropical humid climate conditions through natural ventilation.

From a building science perspective, the Sobokartti Theatre is a useful case for examining the correlation between architectural design, control of air flow and indoor thermal efficiency. The spatial layout, vertical ventilation openings, high roof, and large indoor space provide the environmental conditions for the comprehensive study of passive thermal regulation mechanisms based on integrated field measurements, numerical simulations, and thermal comfort evaluations. This case study was chosen for its historical and cultural significance as well as its scientific relevance as a typical example of climate-responsive vernacular building in Javanese heritage. This study considers the building not as a cultural product but as an environmental system in which the architectural design, the natural ventilation techniques, and the occupants' temperature conditions are combined to generate quantifiable and understandable environmental performance.

Figure 1. Location and Focal points of Sobokartti

2.3. Triangulation framework and field assessment strategy

The methodological structure of this study consists of three distinct strands of evidence that are studied and synthesized simultaneously in the interpretive phase. The triangulation schema is adopted as the basis for CFD modelling, thermal comfort evaluation and evidence integration.

2.3.1. Architectural and documentary analysis

Documentary evidence on the typological evolution of Javanese vernacular theatre architecture was systematically gathered from historical archives and scholarly publications, including the influence of Dutch colonial architectural traditions on local spatial and climate design. The historical and typological basis was built and interpreted from these sources. Field observations and environmental assessments were developed and interpreted.

2.3.2. In-Situ qualitative observation

Site factors, spatial organization, building orientation, construction materials, ornamental systems and architectural typology in relation to passive ventilation efficacy were captured by field observations. Interviews with building managers, cultural practitioners and members of the Sobokartti community provided experiential and culturally contextualized information on the building's ventilation patterns throughout the season. These qualitative results subsequently informed the choice of measurement points and the interpretation of the quantitative results.

2.3.3. Quantitative field measurements and stakeholder interviews

Field measurements are generally accepted as the major empirical method for assessing the interior environmental performance of naturally ventilated buildings in real operation [29], [30] . In heritage contexts, the in situ measurements are especially significant since the inside environment is dictated by the combination of architectural configuration, ambient weather and natural ventilation dynamics. However, physical measurements still reflect the ambient circumstances and do not completely account for the mechanisms responsible for the observed thermal behavior. This gap is filled by the supplemental techniques outlined in Sections 3.4–3.6. To reconcile qualitative views with empirical data, a full field study was carried out at the Sobokartti Theatre to analyze the interior and exterior temperature conditions and the effectiveness of natural ventilation in the building in the tropical humid environment of Semarang. The measured parameters at each measurement point were interior and outdoor air temperature (°C), relative humidity, mean radiant temperature (°C) with a globe thermometer, indoor air velocity (m/s) at 1.1 m (sitting) and 1.5 m (standing), and outdoor wind speed and direction (m/s). Instrumentation included HOBO data recorders, a globe thermometer, and a hotwire anemometer. The measurements were made continuously for a week in the hot season, and descriptive statistics were applied for each parameter.

The qualitative evaluations of the architectural aspects were compared to the quantitative measurements in the relevant places. The data collection was used as the empirical basis for the subsequent CFD simulation, thermal comfort analysis, and evidence integration. In addition to these physical observations, subjective thermal responses were collected using an occupant survey under the same spatial and temporal settings. Three daily time periods, i.e., morning (09:00–12:00), afternoon (12:00–15:00) and evening (15:00–18:00), were considered, and a total of 36 respondents (18 male and 18 female) with an age ranging from 19 to 22 years old filled a structured questionnaire on thermal sensation, thermal acceptability, thermal expectation and air velocity perception in the audience area.

2.3.4. Numerical simulations

The use of computational fluid dynamics (CFD) has become an increasingly popular tool for the study of airflow dynamics and natural ventilation in buildings, including those of history and historic architecture [31], [32]. CFD offers a comprehensive understanding of airflow patterns and ventilation pathways, delivering mechanistic insights that field data alone cannot provide. However, although CFD has been used as a stand-alone analytical tool in previous studies, there have been fewer that explicitly combine simulation with detailed field measurements, thermal comfort assessments, and architectural analysis in a coherent framework. This methodological weakness has implications for the simulation strategy adopted in the present study. A CFD simulation was utilized to analyze the claimed indoor ambient conditions for airflow mechanisms. The computer model was built based on the architectural geometry of the building, and the boundary conditions were derived from the field measurements. The investigation of airflow was aimed at the identification of the main ventilation pathways, vertical airflow structure and the interaction of architectural design with the natural air exchange. Details of the software, turbulence model, mesh, boundary conditions and model validation will be provided.

The CFD gave mechanistic insight into the airflow patterns underlying the observed thermal conditions, supporting the integrative approach presented in the Results and Discussion.

2.4. Approach for thermal comfort assessment

Thermal comfort assessment provides a critical link between the physical indoor environment and occupant-related environmental performance. The interior environmental quality in naturally ventilated buildings has been assessed using widely adopted traditional models like the Predicted Mean Vote (PMV) and adaptive comfort approaches [33]. Each model is based on different assumptions regarding human temperature perception; hence, their joint application is highly useful in studies concerning climate-responsive heritage structures.

In the present study, complementary thermal comfort assessment approaches were applied to evaluate the indoor environmental performance from different perspectives. The primary thermal index used in this study was the operative temperature, which was measured in the field. The occupant-related variables were measured by the PMV analysis, adaptive comfort assessment and the applicable national thermal comfort standard. Rather than being viewed as competing approaches, they were seen as complementary sources of evidence for different aspects of thermal comfort.

The assessment of thermal comfort in the general methodological framework provided the occupant thermal evidence relating the recorded ambient variables and the airflow patterns obtained from CFD to human thermal responses. This integrated evaluation supported the multidisciplinary interpretation presented in the Results and Discussion.

2.5. Evidence integration strategy

Previous research has mainly used field measurements, numerical models, and thermal comfort evaluations or architectural studies as separate and often independent methodological components [33], [32], [34]. Although each approach gives significant insights, examining them separately con-strains our capacity to uncover the complex environmental dynamics of naturally ventilated heritage structures. An integrated approach to building evidence is required for more comprehensive and scientifically sound knowledge. The present study adopted an evidence integration approach where each methodological component contributed a distinct and complementary level of scientific evidence. Historical-typological evidence through archival and ethnographic analysis; physical evidence through field measurements; mechanistic evidence through CFD simulation; occupant thermal evidence through thermal comfort assessment; contextual evidence through architectural interpretation and benchmark comparison. Rather than working independently in the synthesis process, several layers of evidence were methodically combined to strengthen the scientific study of the building's environmental performance. The analytical framework produced in this study is based on this comprehensive methodological approach, which is the conceptual basis for it. This approach improves interpretative robustness by systematically integrating multiple converging sources of evidence, minimizing dependence on one analytical approach, and confirming that conclusions about passive ventilation performances are based on both cultural understanding and empirical validation. This evidence hierarchy supports the scientific interpretations stated in the Results and Discussion.

3. Results

In this chapter, the research results are presented using a progressive analytical structure that aims to show the measured thermal performance in the Sobokartti Theatre as well as the environmental reasons behind that performance. The results are presented hierarchically—starting with the architectural and environmental context, then the field measurements, the behavior of the airflow, and the thermal performance evaluation—rather than as individual datasets or isolated observations, leading to an integrated interpretation through the Five-Lens Triangulation Framework. This sequence permits each layer of evidence to build gradually on the next, allowing the findings to go from direct physical observations toward an integrated scientific interpretation.

3.1. The architectural features and environmental setting

To understand the thermal behavior of a naturally ventilated heritage building, the physical and environmental contexts in which heat transfer and air flow occur must be established. These characteristics are the core physical data on which the following evaluations are based, because thermal performance is primarily determined by the interaction between building geometry, climatic circumstances and architectural arrangements. The Sobokartti Theatre is in a tropically humid climate with continuously high ambient temperatures, high relative humidity, and seasonal changes in the predominant wind direction. In this sense, the architectural reaction to the local climate is an important factor in the building's performance, as the possibility of sustaining appropriate internal thermal conditions depends mostly on the use of passive environmental techniques rather than on mechanical cooling.

3.1.1. Microclimate and site planning

Site planning has a significant influence on the performance of natural ventilation, as the movement of air on all sides of a building is controlled by territorial and structural arrangements, building orientation and the surrounding environment, which also affect prevailing wind and control the movement of air through the building [21]. The main façade of the Sobokartti Theatre faces south, not only to face the major entrance on Dargoweg for public access but also to be strategically used by architect Herman Thomas Karsten to catch the prevailing wind in Semarang from the southwest to the southeast. Karsten orientated the construction south so that the prevailing wind would hit the main façade and funnel the best possible air inside, enhancing natural ventilation. Field observations show a prevailing south-east to north-west wind direction. The wind enters the front at night and the back during the day. This bidirectional behavior was statistically confirmed. Mean external wind speeds around the main façade ranged from 1.5 to 2.0 m/s, demonstrating the important wind pressure on the main building exterior.

Topography and the shape of the street canyon also influence the incoming airflow. The archival archives of the Leiden Library show that in 1931, when it was opened as a people's theatre, Sobokartti was placed in a carefully planned setting framed by generous open ground [35]. The northern boundary is adjacent to Kampung Brondongan for approximately 13.50 m from the building; the eastern boundary is bounded by Karrenweg, the main road for vehicles in the Dutch East Indies period; the southern boundary was previously open space with main access via Dargoweg; and the western boundary was open space approximately 80.00 m from the western edge of the site [35]. Roads and open spaces act as natural ventilation corridors that enable air to travel freely and limit the buildup of pollutants in crowded urban areas [36].

Measured indoor air velocities in zones close to the main façade averaged 1.16–1.18 m/s, which is high enough to support effective natural ventilation, while still within the adaptive comfort range recommended by ASHRAE 55 for naturally ventilated tropical spaces, directly contributing to occupant comfort in this urban ventilation infrastructure. During the measurement period, the outdoor temperature was 35.1°C. The zone near the main façade was 33.1°C, the corridors on both sides averaged 33.0°C and the performance hall was 34.2°C, showing a consistent pattern of thermal moderation from the exterior to the interior. Low shrubs and shade trees on the eastern side have been preserved since the structure was established and reduce infiltration of hot external air by shading, transpiration and evapotranspiration. The collective transpiration of the vegetation also reduces the ambient air temperature, which contributes to microclimate stability and reinforces the building's transitional spatial strategy of catching natural airflow at the building periphery [37].

3.2. Shape, spatial layout and roof configuration

Interior airflow is controlled by the building's circulation patterns, spatial layout, and aperture arrangement, which should be designed largely around the provision of adequate interior airflow rather than aesthetics alone [38]. The Sobokartti building contains a 24.00 m x 22.87 m rectangular room without partitions (Figure 2). The spatial qualities of traditional Javanese architecture include parallel apertures, a few interior partitions, high ceilings, and continuous internal corridors on the right and left sides, all of which enable passive ventilation.

The long building uses linear corridors to conserve energy through natural ventilation and minimize solar heat gain [39]. The spatial relationship between lower air inlets and upper ventilation outlets indicates the potential development of buoyancy-assisted airflow. This architectural arrangement allows warm indoor air to migrate upward while cooler outdoor air is continuously introduced through lower openings, creating a passive ventilation mechanism that is expected to contribute to indoor thermal regulation. In high-temperature, high-humidity tropical settings, buildings should avoid internal barriers to airflow. This goal is achieved in effect by the open layout of Sobokartti: field measurements indicated typical indoor air velocities of 0.54–0.68 m/s in the main performance hall with peak speeds of up to 1.2 m/s if measured near aligned apertures during periods of vigorous outdoor wind. These values are within the range of adaptive comfort of naturally ventilated tropical spaces, in which high air movement offsets high air temperature and minimizes thermal discomfort. Occupant interviews showed that users engaged in sedentary arts activities (including Gamelan practices) found circumstances thermally tolerable during measured periods without mechanical cooling.

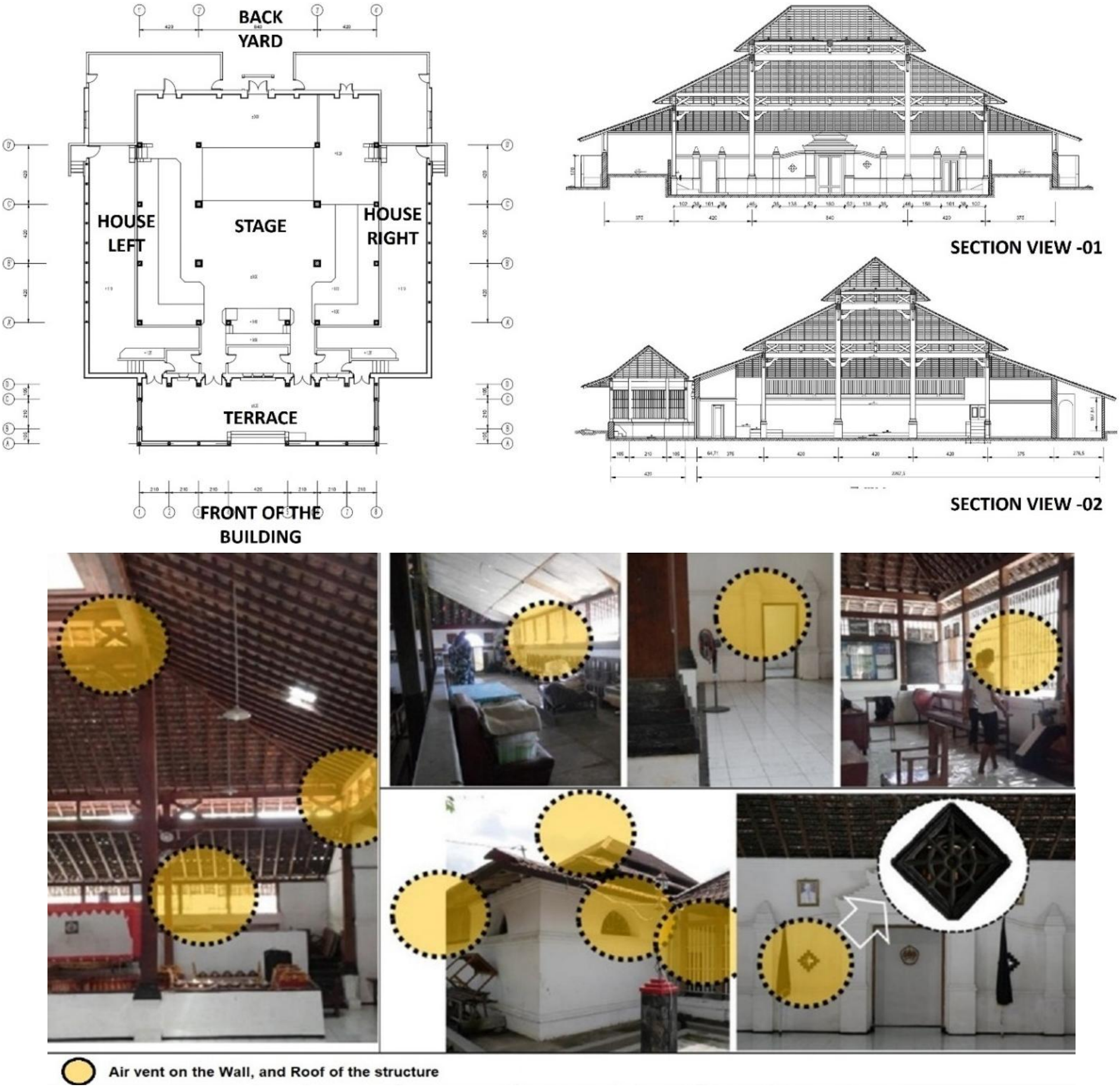

Figure 2. Building geometry, floor plan, section, and principal ventilation elements

The most important environmentally architectural aspect is the multistage roof (tumpang sari). The Joglo style roof supported by wooden pillars (saka guru), as the typology of Pendhapa, has been used as a natural roofing ventilation system, apart from being a spiritual and visual icon of Javanese culture [40]. The three roof strata reach 5.00 m, 7.50 m and 11.00 m, respectively, generating a significant height difference that is an active driver of stack-effect ventilation. Field studies indicated that air velocity near the uppermost roof opening averaged 0.6-0.9 m/s even when lower-level windows were partially closed, confirming the effectiveness of the roof as a passive exhaust mechanism. The Pendhapa framework, which is usually an open community arena for Gamelan, Wayang Kulit, and Wayang Wong performances, was combined by Karsten with European theatrical concepts [41]. The integration was not only of cultural and programmatic intent but also generated a spatial typology that was innately conducive to passive airflow and occupant comfort. The physical evidence includes the architectural parameters indicated above, which form the basis for further analysis of the recorded thermal performance, airflow behavior and thermal comfort.

3.3. Measured indoor thermal environments

According to the architectural characterization in previous section, the inside thermal environment was assessed by detailed field measurements to get the empirical proof of the environmental performance of the structure. Four main environmental parameters, for example, operative temperature (To), air temperature, relative humidity and air velocity, were simultaneously monitored at representative sites across the inhabited area to capture the combined impact of climatic conditions and natural ventilation. The indoor air temperature showed a distinct diurnal variation, matching the external climatic cycle, progressively increasing from morning to afternoon and dropping towards the evening. However, the internal thermal response was continuously reduced as compared to the outer environment, suggesting the building envelope and natural ventilation system helped reduce the intensity of daytime heat accumulation (Figure 3).

The operative temperature (To) accounts for the combined effects of the air temperature and the mean radiant temperature. It was constantly lower than the relevant outdoor condition during the measurement period, indicating that the building was able to moderate the thermal exposure, despite the variation of the external conditions. Such behavior suggests that indoor thermal conditions are not only a function of the ambient temperature but also the combined effects of architectural shading, heat storage, radiative exchange, and constant natural ventilation. Although the air temperature increased during the day, the relative humidity remained rather consistent, indicating that the continuous air exchange avoided the accumulation of excessive moisture while retaining the humidity of tropical climes. Relative humidity alone does not determine thermal comfort, but its interplay with air temperature and air movement is vital in determining occupants' thermal perception.

Air velocity data showed geographical and temporal diversity, related to the interaction of outdoor wind conditions with the building's ventilation channels. The zones directly associated with the main ventilation apertures were characterized by stronger air circulation in comparison with internal sections situated far from airflow inlets. These small variations, nevertheless, did not prevent the maintenance of observable airflow within the inhabited space, therefore supporting the continuous convective heat removal. Figure 4 shows the spatial distribution of air velocity.

The provision of openings, such as doors, windows, meshes, and roof apertures, directly controls the supply, circulation, and outflow of air [40]. The front façade has a porosity of 33%; the left and right sides are 41%; and the back is 25%. The side windows are located at 1.50 m above the floor level, parallel to the typical breathing height of the Indonesian occupants. This configuration provides quantifiable cross-ventilation, with indoor air velocities on the lateral flanks averaging 0.27-0.29 m/s at seated breathing height (1.1 m) and 0.28-0.44 m/s at standing height (1.5 m) under moderate outdoor wind, all within the ASHRAE 55 adaptive comfort threshold for naturally ventilated tropical environments [42]. The average temperature difference between the entrance and outlet sides was 0.7-1.1°C, indicating a satisfactory degree of thermal exchange of the performance hall driven by cross-ventilation. It is necessary to evaluate the four measured factors together for a proper interpretation of the indoor environment. The thermal conditions observed are the result of the combined interaction of temperature, humidity, air movement and radiation influences that work simultaneously within the architectural arrangement. Thus, these field data provide the first empirical layer of information upon which further assessments of airflow mechanics and thermal moderation are built.

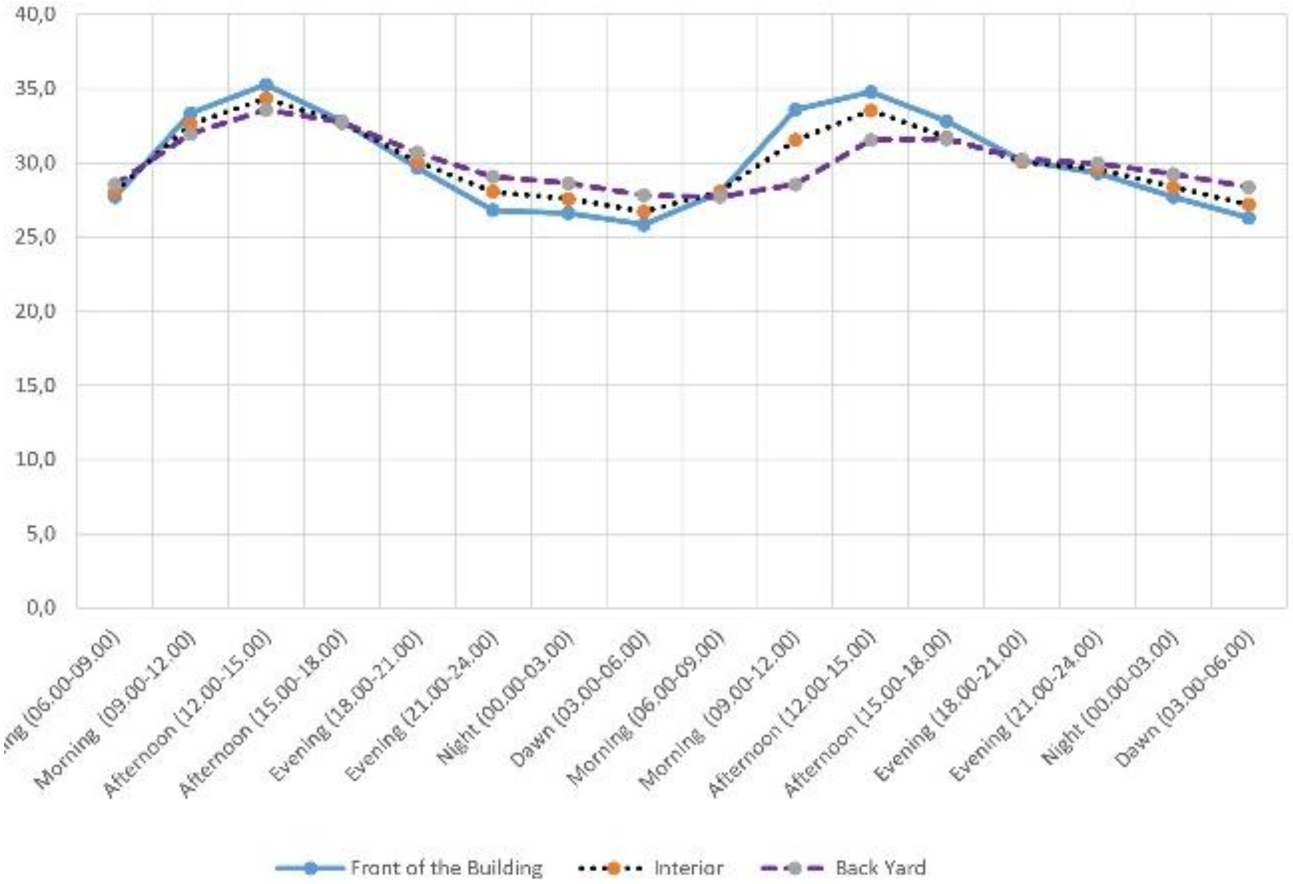

Figure 3. Spatial distribution of the measured indoor air velocity

3.4. Mechanism of the airflow behavior and thermal moderation

Field measurements describe the temperature properties of the indoor environment but do not explain in detail the physical processes that produce those conditions. Therefore, in this section, numerical simulation of airflow and thermal performance assessment are integrated to unveil the principles gradually driving natural ventilation and indoor temperature regulation.

3.4.1. Airflow pattern from CFD

Natural ventilation is basically a flow mechanism, rather than just an airflow quantity. Therefore, the environmental impact of natural ventilation is not only a function of the amount of air movement but also of the arrangement of the airflow paths in the architectural space. A CFD simulation was used to supplement field measurements by illustrating airflow patterns that were not directly observable during in-situ measurements.

The results of the simulation show that the outdoor air enters the building mostly through the apertures in the bottom wall and then is distributed in the occupied zone. The incoming air, as it passes through the internal spatial configuration, is redirected upwards to the higher interior volume and then discharged through the upper ventilation apertures beneath the roof—a circulation pattern consistent with a vertically organized natural ventilation system that supplements horizontal cross-ventilation. The air velocity was measured as 0.46 m/s in the first roof-level opening, 0.53 m/s in the second level and 0.40 m/s in the top level, which confirms the gradual expulsion of the hot air through the roof levels.

The high porosity of the front façade (33%) allows the prevailing southwest-to-southeast breezes to interact directly with the interior, while the moderate side porosity (41%) supports cross-ventilation along the whole width of the performance hall. The simplest direct way of ensuring adequate cross-ventilation is to have side openings located on opposite sides of the building [43]. The multistage Joglo roof also acts as a wind scoop and a driver of the stack effect. The height differential between the three roof levels produces differential pressures that draw air up and out through the uppermost apertures, replacing it with cooler external air drawn in through lower openings according to Bernoulli's principle [44]. Another indication that buoyancy-assisted ventilation is occurring together with wind-driven ventilation is the upward motion of the warmer air inside the building.

The airflow pattern simulated shows continuous airflow over the occupied space; however, local velocities are variable, with larger velocities around the major apertures and lower, but observable, airflow intensity in the more interior zones. The continuity of the airflow in general suggests the effectiveness of the architectural design in terms of air exchange in the indoor environment, rather than producing isolated stagnant zones. Results can be seen Figure 4 and Table 1.

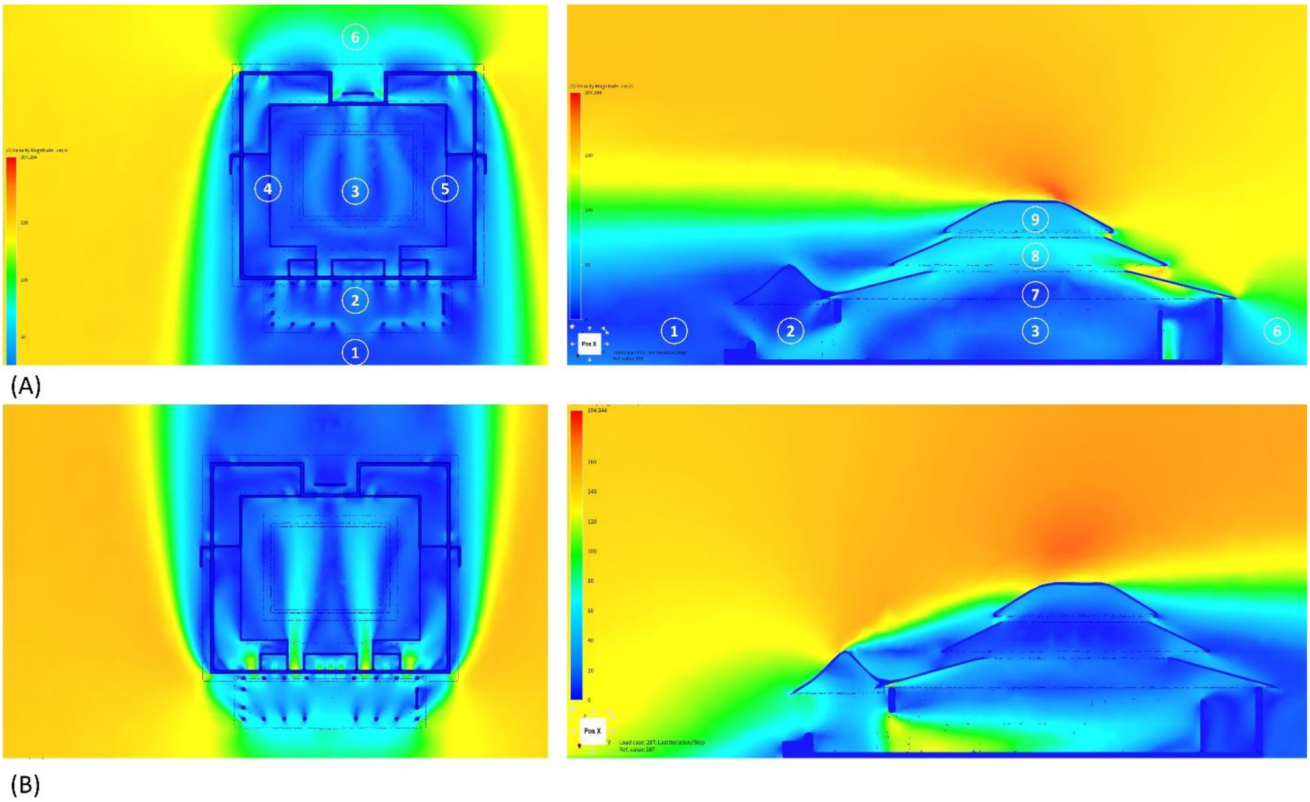

Figure 4. CFD-derived airflow velocity vectors and streamlines: air movement in the morning (A), Air movement in the evening (B)

Table 1. Morning and evening air velocity distribution

	Front of the Building	Terrace	Stage	Lowes Beam	Middle Beam	Ridge Pole	Back Yard
	(1)	(2)	(3)	(7)	(8)	(9)	(6)
Morning	1.22	0.46	0.54	0.64	0.72	0.43	0.69
Evening	1.22	0.60	0.66	0.57	0.53	0.52	0.53

Table 2. A three-layer comparison of thermal evidence (PMV ASHRAE- SNI)

	Front of the Building	Terrace	Stage	House Left	House Right	Back Yard
	(1)	(2)	(3)	(4)	(5)	(6)
Morning	1.19	0.46	0.60	0.27	0.29	0.82
Evening	1.20	0.44	0.66	0.29	0.28	0.46

3.4.2. Thermal moderation

This section provides a full evaluation of indoor thermal comfort in the surveyed heritage building, including objective PMV measurements, occupants' subjective thermal sensation voting (TSV) and adaptive comfort indicators for three observation periods: morning, afternoon and evening. Table 2 shows a three-layer comparison of thermal evidence (PMV/ASHRAE, SNI Indonesia and subjective occupant experience) by gender (male/female) for three time periods (morning, midday, and afternoon). The aggregate PMV increased from 0.7 (morning) to 2.2 (midday) and 2.1 (afternoon), which put the midday and afternoon conditions in the "warm" category according to both ASHRAE and SNI Indonesia standards. The measured values of PMV showed that the PMV values increased from 0.7 in the morning to 2.2 and 2.1 in the afternoon and nighttime, respectively, which indicated a progressive increase in thermal stress during the day. A PMV of 0.7 corresponds to a mildly warm thermal experience on the ASHRAE thermal sensation scale, and a PMV above +2.0 corresponds to a warm thermal sensation. Hence, the circumstances in the afternoon and evening were outside the comfort range (−0.5 to +0.5), indicating significant heat stress during the peak occupancy hours

The subjective sensation voting showed a strong gender divergence that was not captured in the single aggregate PMV value. By noon, 67% of male respondents reported feeling "slightly warm" compared to only 22% of females, while 56% of females felt thermally neutral compared to 22% of males, despite both groups being subjected to nominally comparable PMV circumstances (2.2). This pattern was reversed in the afternoon, where male respondents reported considerably cooler sensations (33% "slightly cool") than females. Thermal acceptability ratings support the adaptive capacity of occupants for all observation periods, most respondents assessed the thermal environment as acceptable, with acceptance rates ranging from 67% to 89%; the greatest approval rate was recorded for female in the afternoon (89%). The high acceptability was maintained even with PMV values above +2.0, which points to a well-documented problem in the area of adaptive comfort: thermal acceptability in naturally ventilated buildings is determined not only by the physical environmental parameters but also by the expectations of the occupants, their cultural background and their acclimatization to the local climate.

Thermal expectation and air velocity preference were more in line with the midday PMV peaks than the afternoon circumstances, which further supports air movement as the key adaptive lever regardless of gender. For all three standards, the main trend is the same: morning is near the comfort threshold ("comfortable at the upper threshold", PMV 0.7 — slightly warm), while midday (PMV 2.2) and afternoon (PMV 2.1) are in the "warm" category according to both ASHRAE and SNI. Subjective TSV responses were only partly in agreement with the PMV predictions, consistent with the adaptive comfort theory. In the morning, around one half of the respondents indicated thermal neutrality, and only one third felt the environment was a little warm, although the PMV predicted a slightly warm state. This divergence shows that the inhabitants had acclimatized by behavioral changes, clothing adjustment or physiological acclimatization to the local tropical environment.

The responses of thermal preference support this adaptive interpretation. In the morning, 72% to 100% of respondents favored cooler circumstances; in the afternoon, it was 61–100%, even though many at the same time rated the climate as satisfactory. Only a tiny proportion (about 6% in one afternoon grouping) requested warmer circumstances. This pattern suggests that residents were physiologically tolerant of existing heat levels but felt that overall comfort would be better by improved cooling. Air movement was shown to be an especially important variable. In the afternoon, all responders both genders wanted the air velocity raised. The demand for more air movement was still high in the evening, especially for male (44%), while more than half of females were happy with the air movement at that moment. The results demonstrate that focused enhancement of air velocity, either optimized natural ventilation or additional mechanical circulation, is a high-impact, low-energy approach to increasing thermal comfort without lowering the interior air temperature.

The results generally show a strong and constant disagreement between the PMV-based projections and the occupants' subjective heat sensation. The PMV model showed that the audience hall was thermally warm, especially in the afternoon and evening, yet a large percentage of the occupants reported neutral sensations and acceptable conditions. This gap reinforces the limits of using the PMV model in isolation in the context of naturally ventilated or semi-open heritage buildings in tropical contexts where occupants exhibit significant physiological, behavioral and psychological adaptive ability.

The findings carry major implications for heritage protection and the sustainable development agenda. Instead of resorting to energy-intensive mechanical cooling that may compromise the architectural originality and spatial integrity of heritage buildings, passive environmental techniques should be used. Specific interventions include optimizing cross-ventilation pathways, introducing ceiling or wall fans to improve effective air movement, re-arranging building openings for better airflow and minimizing solar heat gain with shading elements consistent with the building's heritage character. These approaches link the enhancement of thermal comfort to the conservation aims at the heart of sustainable heritage management and the well-being of the occupants.

The thermal moderation of the Sobokartti Theatre is achieved by the combined application of two main passive environmental mechanisms: stack-effect (buoyancy-driven) ventilation and wind-driven cross-ventilation [45]. The stack effect is a function of the density differential between the indoor and external environments. It causes hot inside air to flow upward through higher openings, creating a pressure gradient that causes cooler exterior air to be pulled in through lower openings continually. The differential air pressure across the building envelope induces wind-driven ventilation in relation to the strategic location and dimensioning of façade openings. These systems work together to create a continuous and perceivable flow of air within the building to increase thermal comfort and air quality and minimize dependence on mechanical cooling. Thermal moderation should therefore be viewed as an overall response of the building and not an isolated influence of any external condition.

Table 3. Summary of indicators of thermal performance (PMV ASHRAE- SNI)

			The House Morning Male	Female	Midday Male	Female	Afternoon Male	Female
	PMV Thermal Evidence							
1	PMV		0,7		2,2		2,1	
2	Sensation ASHRAE		Slightly Warm		Warm		Warm	
	SNI Thermal Evidence							
3	SNI Indonesia		comfortable at the upper threshold		warm at the upper threshold		warm at the upper threshold	
	Occupant Thermal Evidence							
4	THERMAL Sensation	Slightly Warm	33% (6/18)	44% (8/18)	67% (12/18)	39% (7/18)	50% (9/18)	11% (2/18)
		Neutral	50% (9/18)	39% (7/18)	22% (4/18)	56% (10/18)	28% (5/18)	67% (12/18)
		Warm	17% (3/18)	17% (3/18)	11% (2/18)	6% (1/18)		22% (4/18)
		Slightly Cool					22% (4/18)	
5	Thermal Acceptability	No	17% (3/18)	28% (5/18)	28% (5/18)	11% (2/18)	33% (6/18)	22% (4/18)
		Yes	83% (15/18)	72% (13/18)	72% (13/18)	89% (16/18)	67% (12/18)	78% (14/18)
6	Thermal Expectation	Cooler	72% (13/18)	72% (13/18)	100% (18/18)	61% (11/18)	22% (4/18)	39% (7/18)
		Warmer				6% (1/18)	22% (4/18)	11% (2/18)
		Neutral	28% (5/18)	28% (5/18)		33% (6/18)	56% (10/18)	50% (9/18)

			The House					
			Morning		Midday		Afternoon	
			Male	Female	Male	Female	Male	Female
7	Air Velocity Perception	Need more wind	67% (12/18)	72% (13/18)	100% (18/18)	50% (9/18)	33% (6/18)	44% (8/18)
		Neutral	33% (6/18)	28% (5/18)		50% (9/18)	67% (12/18)	56% (10/18)

3.4.3. Architectural robustness to airflow

The consistent airflow organization found in the field measurements and CFD simulations shows that the environmental performance of the Sobokartti Theatre does not depend on isolated architectural elements but on the robustness of the overall ventilation system. This feature is named 'Architectural Airflow Robustness' in the present study, which is the ability of an architectural configuration to preserve effective airflow pathways under naturally varying environmental conditions.

This robustness is due to the coordinated interactions between the lower air inlets, the large interior volume, the raised roof shape, and the upper ventilation outlets. These components are not working in isolation but constitute part of an integrated ventilation system, which can provide continuous exchange of air even when external climatic conditions vary over time. The roof is the most likely part of the traditional Javanese design to maximize ventilation, which has a profound effect on air circulation within the house [46]. The multi-stage Joglo roof of the Sobokartti building is a clever combination of cultural expression and quantitative environmental performance that continues to provide thermal and comfort benefits under the tropical humidity conditions of Semarang. The findings therefore suggest that the performance of adequate natural ventilation should be assessed not only by the instantaneous amplitude of the air flow but also by the resilience of the architectural arrangement of air flow to support environmental performance over time. (See Figure 5).

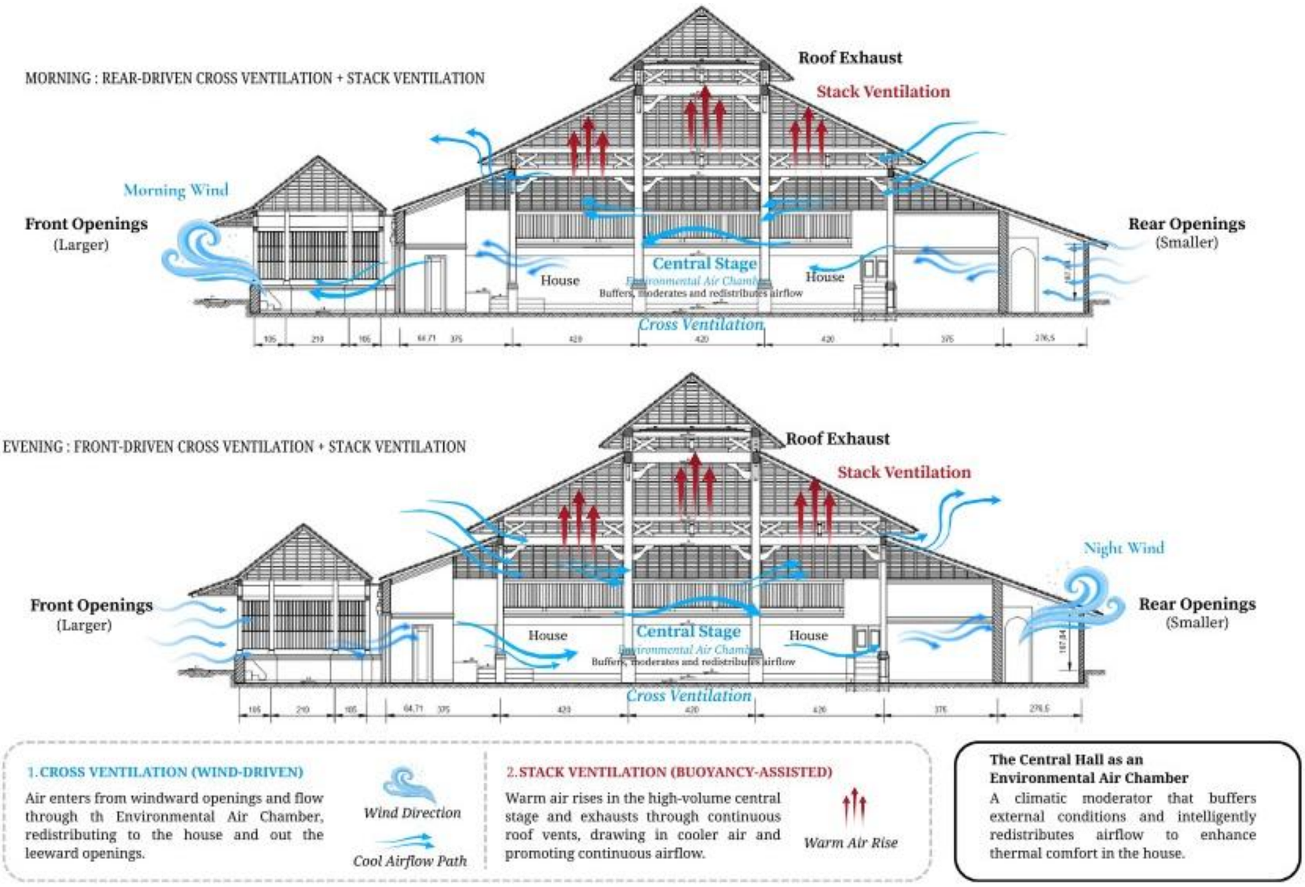

Figure 5. Conceptual diagram of architectural airflow robustness

3.4.4. Five-lens triangulation framework

The environmental performance of a naturally ventilated heritage building cannot be satisfactorily elucidated by a single source of evidence. Thermal comfort assessment evaluates occupant-related performance; field measurements characterize indoor environmental conditions; CFD simulation elucidates airflow mechanisms; architectural observation elucidates the physical configuration; and benchmark references provide an external basis for comparison. Although each category of evidence describes only one aspect of building performance, collectively, these types of evidence enable a more comprehensive and scientifically robust interpretation. As a result, the present investigation employs a five-lens triangulation framework, which entails the interpretation of the building's environmental performance from five complementary perspectives: physical evidence, mechanistic evidence, occupant thermal evidence, architectural evidence, and benchmark evidence. As illustrated in Figure 8, these five lenses operate as mutually reinforcing sources of evidence that collectively reduce interpretative uncertainty, rather than operating hierarchically. The physical lens establishes the empirical foundation through in situ environmental measurements. The mechanistic lens elucidates the process by which the thermal conditions observed are generated by airflow patterns through the use of CFD simulation. By assessing indoor thermal performance through operative temperature, PMV, adaptive comfort assessment, and the pertinent Indonesian National Standard (SNI), the Occupant Thermal Lens incorporates internationally established predictive models with context-sensitive thermal acceptability. The Benchmark Lens contextualizes the findings within the broader body of scientific literature and recognized performance references, whereas the Architectural Lens interprets the ways in which building configuration enables passive environmental regulation. The convergence of these five complementary lenses consistently supports the interpretation that the observed thermal performance is the result of the integrated interaction between architectural design and natural ventilation, rather than of isolated environmental variables. This integrated evidence serves as the analytical foundation for the more extensive scientific discourse that will be discussed in the subsequent section.

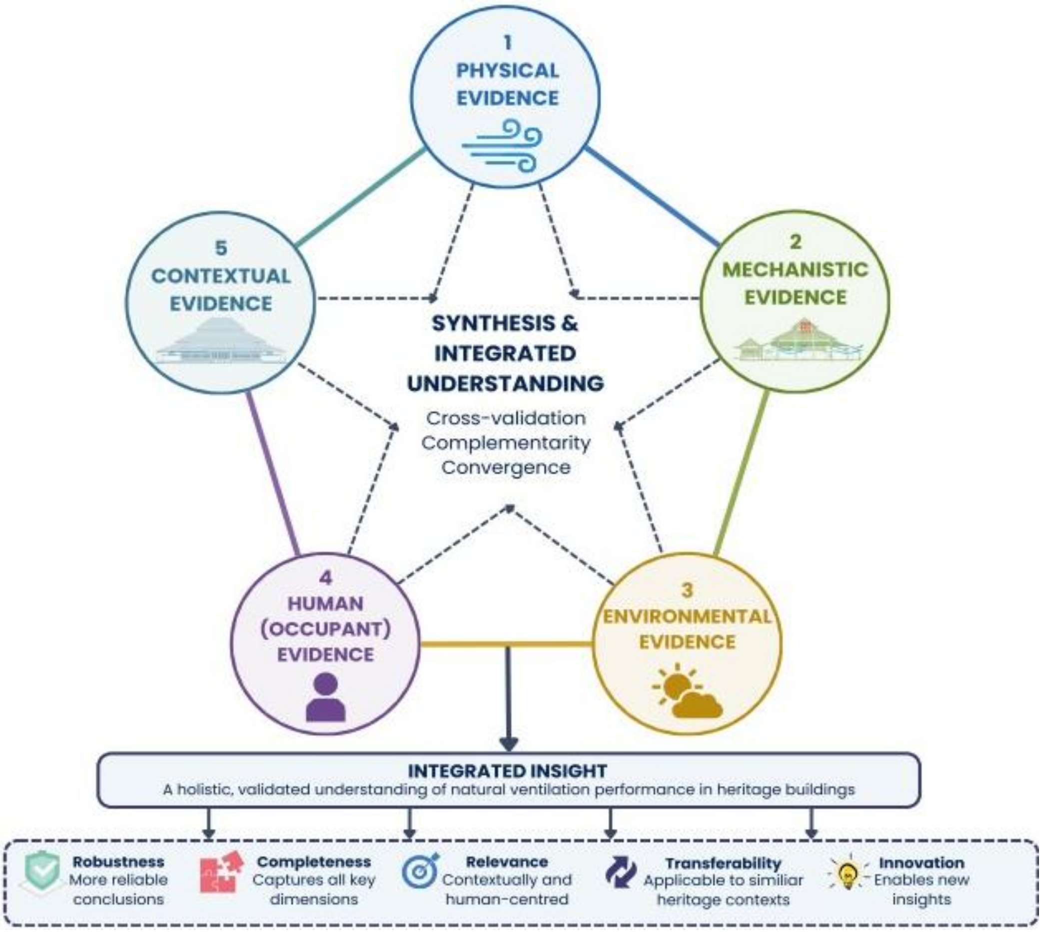

Figure 6. Five-lens triangulation framework

4. Discussion

This chapter presents the key discoveries and wider contributions that have emerged from the study of the Sobokartti Theatre, a naturally ventilated tropical heritage building steeped in the Javanese vernacular architectural tradition.

4.1. Scientific interpretation of integrated evidence

The integrated findings demonstrate that the observed indoor thermal environment cannot be adequately explained by individual environmental parameters alone. The measured air temperature, operative temperature, air velocity, CFD-derived airflow patterns, and thermal comfort assessments collectively indicate the presence of a coordinated environmental mechanism through which the Sobokartti Theatre continuously moderates indoor thermal conditions — a shift from analyzing isolated variables toward understanding the building as a climate-responsive environmental system. A central finding is that natural ventilation functions as the primary environmental regulator governing indoor thermal performance. The measured reduction in operative temperature, combined with the systematic spatial distribution of air movement confirmed through CFD simulation, demonstrates that airflow is architecturally organized rather than randomly distributed. The observed thermal performance should therefore be interpreted as the environmental consequence of an integrated natural ventilation mechanism embedded within the Javanese vernacular spatial con-figuration.

The interpretation is further strengthened by the convergence of multiple independent sources of evidence. Field measurements provide direct physical observations; CFD simulation explains the airflow mechanisms responsible for heat removal; thermal comfort assessments — including Operative Temperature, PMV, and adaptive comfort evaluation based on ASHRAE Standard 55, and the Indonesian National Standard (SNI) — evaluate environmental implications from the occupants' perspective. Rather than competing, these approaches offer complementary perspectives that collectively support the same scientific interpretation.

An important implication is that internationally established predictive models and locally adapted comfort criteria should not be regarded as mutually exclusive. PMV provides a physics-based pre-diction of thermal sensation, whereas adaptive comfort approaches and SNI incorporate the adaptive capacity of occupants in specific climatic conditions. The present study accordingly employs these as complementary components within the Occupant Thermal Evidence layer, enabling com-prehensive evaluation without privileging any single assessment method. Taken together, these findings indicate that the environmental performance of the Sobokartti Theatre is best understood as an emergent property of the interaction between Javanese vernacular architectural design, natural ventilation, and occupant–environment relationships — providing the scientific basis for understanding how climate-responsive architectural configurations continue to perform under contemporary tropical conditions.

4.2. Natural ventilation as an integrated environmental regulator

Natural ventilation is frequently evaluated through isolated indicators such as air change rate, air-flow velocity, or indoor temperature reduction. The findings of the present study, however, indicate that the environmental role of natural ventilation in the Sobokartti Theatre cannot be fully under-stood when these variables are interpreted independently. Instead, natural ventilation should be understood as an integrated environmental regulator that simultaneously governs airflow organization, heat transfer, thermal stability, and occupants' thermal experience.

The CFD simulation confirms that the building promotes a vertically organized airflow system in which outdoor air enters through lower openings, circulates across the occupied zone, and is dis-charged through upper ventilation outlets beneath the multistage Joglo roof. This organization continuously removes accumulated indoor heat while maintaining measurable air movement through-out the performance space through coordinated convective and buoyancy-assisted processes. This mechanism is directly reflected in the measured thermal performance: indoor operative temperature remained consistently below the outdoor condition during periods of maximum daytime heat exposure (Table 4), and locations with greater air movement generally exhibited more favorable PMV values than areas with lower airflow intensity. The overall pattern consistently confirms that natural ventilation contributes directly to reducing occupants' thermal exposure.

The environmental contribution of natural ventilation extends beyond instantaneous thermal com-fort. Through Thermal Moderation, the building continuously attenuates thermal fluctuations rather than eliminating heat entirely — a behavior reflecting the interaction between airflow organization, architectural geometry, roof configuration, and heat dissipation processes operating simultaneously within the building envelope. Additionally, through Architectural Airflow Robustness, the coordinated interaction among lower air inlets, interior spatial volume, elevated roof geometry, and upper ventilation outlets sustains continuous airflow pathways under naturally varying environ-mental conditions.

These findings reinforce the view that naturally ventilated heritage buildings should not be evaluated solely through conventional thermal performance indicators but through an understanding of natural ventilation as an integrated mechanism linking airflow behavior, thermal regulation, occupant comfort, and architectural configuration into a coherent environmental system — an integral dimension of the embedded climatic intelligence preserved within Javanese vernacular architecture.

4.3. Multidisciplinary implications for heritage building conservation

The findings of the present study demonstrate that the environmental value of the Sobokartti Theatre extends beyond its architectural appearance or historical significance. The measured thermal performance, supported by airflow simulation and multiple thermal comfort assessments, indicates that the building embodies a form of climatic adaptation that remains functionally relevant under contemporary environmental conditions. Heritage conservation should therefore be understood not only as the preservation of physical fabric but also as the preservation of the environmental knowledge embedded within historic architecture. From a Building Science perspective, the observed indoor thermal performance emerges from the coordinated interaction between architectural configuration and natural ventilation rather than from isolated environmental variables, reinforcing the importance of evaluating heritage buildings as integrated environmental systems.

From an architectural perspective, passive environmental performance is inseparable from spatial composition. Features such as the elevated Joglo roof geometry, vertically organized ventilation pathways, the open Pendhapa derived spatial volume, and strategically positioned openings collectively form a climate-responsive system whose effectiveness lies not in individual elements but in their coordinated interaction. From a conservation perspective, the environmental performance of historic buildings represents an additional dimension of heritage value deserving systematic documentation and scientific vali-dation. Traditional conservation practice has primarily focused on preserving historical authenticity, material integrity, and architectural character. While these aspects remain fundamental, the pre-sent findings indicate that environmental performance should also be recognized as an essential component of heritage significance, reflecting the climatic intelligence accumulated through generations of Javanese architectural adaptation.

Accordingly, heritage conservation should preserve not only the physical authenticity of historic buildings but also the embedded climatic intelligence they embody. Where physical structures deteriorate, the environmental knowledge they contain should first be scientifically identified, vali-dated, and transferred to future climate-responsive design — transforming conservation from the protection of historical artefacts into the preservation of transferable environmental knowledge capable of informing sustainable architectural practice. These implications also confirm that understanding environmental performance in heritage buildings cannot rely on a single disciplinary perspective. Multidisciplinary collaboration among Architecture, Building Science, thermal comfort analysis, and heritage conservation should be regarded not merely as a methodological preference but as a scientific necessity for comprehensively under-standing climate-responsive heritage architecture.

4.4. Methodological contribution: five-lens triangulation framework

Beyond its empirical findings, the present study proposes a methodological contribution through the Five-Lens Triangulation Framework, designed to integrate multiple complementary sources of evidence into a coherent scientific interpretation of naturally ventilated heritage buildings. The rationale arises from the recognition that no individual method can fully explain the complexity of such buildings. Field measurements describe physical indoor conditions but cannot reveal governing airflow mechanisms. CFD simulation explains airflow organization but does not indicate occupants' thermal perception. Thermal comfort assessments evaluate environmental acceptability from the human perspective but require reliable environmental measurements as input. Architectural analysis explains the physical configuration responsible for environmental behavior, while benchmark references position findings within the broader body of scientific knowledge.

Within this framework:

- The Physical Lens establishes the empirical basis through in-situ measurements of indoor environmental parameters.
- The Mechanistic Lens explains airflow behavior through CFD simulation.
- The Occupant Thermal Lens evaluates thermal performance through Operative Temperature, PMV, and adaptive comfort assessment following ASHRAE Standard 55, and the Indonesian National Standard (SNI) — integrating international predictive models with locally relevant thermal acceptability criteria.
- The Architectural Lens interprets how building configuration enables passive environmental regulation.
- The Benchmark Lens compares findings with existing scientific evidence and recognized performance criteria.

Importantly, the proposed framework does not replace existing analytical methods, standards, or thermal comfort models. It provides a structured strategy for integrating complementary forms of evidence into a scientifically coherent interpretation — functioning as an evidence integration strategy rather than a new thermal comfort model. Although developed within the context of a tropical Javanese vernacular heritage building, its conceptual structure may provide a transferable analytical pathway for future investigations of naturally ventilated buildings where multiple forms of environmental evidence require systematic integration.

4.5. Towards a hierarchy of scientific abstraction

The progression of the present study illustrates that scientific understanding is not established through isolated observations but through systematic evidence integration and conceptual refinement. This progression forms what may be described as a Hierarchy of Scientific Abstraction.

At the first level, direct observations provide measurable physical evidence of the indoor environment, establishing the empirical foundation for subsequent analyses. At the second level, airflow simulation explains the physical mechanisms responsible for measured conditions, transforming descriptive observations into mechanistic understanding. The third level integrates complementary evidence — thermal comfort assessment, architectural interpretation, and benchmark comparison — to strengthen interpretative reliability through triangulation. At the highest level, these integrated findings are synthesized into broader conceptual contributions concerning climate-responsive Javanese vernacular architecture, natural ventilation, and heritage conservation.

Within this hierarchy, scientific interpretation is not generated by introducing increasingly com-plex analytical techniques but by progressively increasing the explanatory power of the available evidence. The strength of a scientific contribution depends not merely on the quantity of collected data but on the consistency with which multiple independent sources of evidence converge toward the same interpretation. The present study thereby demonstrates that the environmental performance of the Sobokartti Theatre should be understood as an emergent property arising from the interaction among Javanese vernacular architectural configuration, natural ventilation, tropical climatic context, and occupant environment relationships — a conclusion that extends beyond this specific case study and pro-vides a conceptual basis for analyzing comparable climate-responsive heritage buildings through evidence-based approaches.

More broadly, the proposed hierarchy offers a structured pathway for future Building Science investigations seeking to move from descriptive performance evaluation toward deeper scientific understanding, encouraging researchers not only to measure environmental performance but to un-cover the climatic intelligence embedded within historic architecture and translate that knowledge into future climate-responsive and sustainable design.

5. Conclusions

This study investigated the environmental performance of the Sobokartti Theatre, a naturally ventilated tropical heritage building, by integrating field measurements, CFD simulation, thermal comfort assessment, architectural analysis and benchmark evidence within a unified five-lens triangulation framework. The findings suggest that the indoor temperature conditions are not driven by individual environmental variables but by the concerted combination of architectural configuration, natural ventilation and occupant-environment connections. The CFD simulation showed a vertical arrangement of the ventilation system ensuring continual air exchange and heat removal. The measured indoor environment was always characterized by moderated conditions with respect to the outdoor climate. The convergence of these separate streams of evidence points to the operation of the building as an integrated passive environmental system, attenuating thermal stress through combined impacts of airflow organization, spatial layout and architectural geometry. This technique is called 'thermal moderation' in this study. This interpretation is further supported by the integration of physical, mechanistic, occupant thermal, architectural and benchmark evidence that this performance is the result of an embedded climate-responsive architectural strategy rather than the outcome of any specific environmental parameter. The results should be interpreted in the context of the study, which is a cross-sectional, single-case study conducted in a defined climatic and seasonal window. More general statements will require comparing investigations across various heritage typologies, climatic locations and seasons. Furthermore, future studies should expand the five-lens framework to include long-term monitoring, observation of occupant behavior, and analysis of building energy use. It should also explore the extent to which the climatic intelligence of traditional architecture might contribute to low-energy, climate-sensitive design beyond the realm of heritage conservation. Ultimately, the issue is not just the conservation of historic buildings, but also the systematic documentation and scientific validation of the environmental knowledge they embody. In this sense, conservation is not only about protecting the past but also about educating the future.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

Eddy Prianto contributed to the conceptualization of the research, development of research instruments, methodology design, and data analysis, interpretation of results, manuscript preparation, and correspondence with the journal. Bharoto Bharoto contributed to the development of the literature review, data collection, and data validation, interpretation of results, data analysis, and manuscript preparation. All authors read and approved the final version of the manuscript. All authors approved the final version of the manuscript.

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